UNIVERSITY OF MISKOLC
MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES
Head of the doctoral school:
Prof. Dr. Péter Szűcs
Professor

Propped Hydraulic Fracture Analysis

New scientific achievements of Ph.D. Thesis

Author: TAMÁS LENGYEL
MS in Petroleum Engineering

Advisor: PROF. DR. ISTVÁN LAKATOS
Professor Emeritus

Miskolc, 2022

1. INTRODUCTION & TOPIC RELEVANCE

Due to the volatile macroeconomic environment, the Petroleum Industry has faced challenging periods in the last years or even decades. The oil price shock in 2014, the changing but continuously increasing demand for oil and gas, the transformation of oil refining: the shift from fuel-based products to more sophisticated petrochemicals with higher added value, the spread of electrical vehicles (EV) are factors that emphasize hydrocarbon production optimization and made production intensification technologies as vital as it has never been.

Hydraulic fracturing is one of the most common improved oil recovery (IOR) methods used in the Upstream Division of the Petroleum Industry to enhance well productivity in tight gas/oil or shale gas/oil reservoirs (Denney, 2010). The purpose of fracturing is production intensification by creating high conductive, propped fractures that provide a larger inflow surface than the cylindrical area of an ordinary well (Economides & Nolte, 2000). The fracturing procedure is controlled on the surface and executed by high-power hydraulic pumps boosting the hydraulic fluid to exceed the formation breakdown pressure at the bottom hole. **Fig. 1** represents the schematic of hydraulic fracturing. The fracking fluid contains ~ 99 % water and ~ 1 % additives to increase the dynamic viscosity, thus preventing fluid leak-off and enabling pressure boost at the bottom hole. This hydraulic fluid pressure initiates the formation to break. Meanwhile, the fracture starts to propagate according to the petrophysical properties of the given formation.

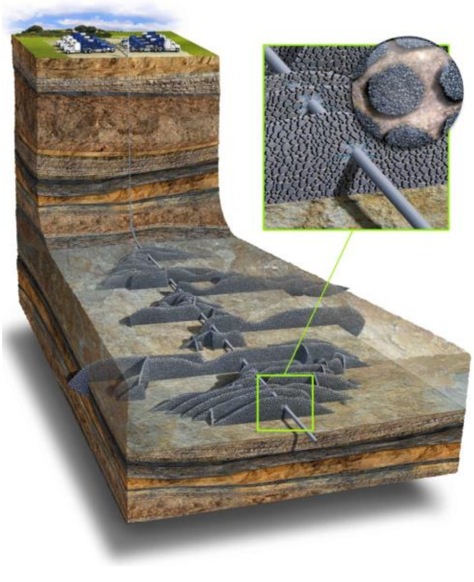

Fig. 1 Schematic of hydraulic fracturing (Schlumberger, 2021)

The proppant is a granular media with high porosity mixed with the fracturing fluid to prop the fracture and prevent formation closure that would result in an ineffective stimulation (Barree & Conway, 1995).

The phenomenon investigated during the research occurs after fractures are created and hydraulic pumps are stopped entailing the hydraulic fluid pressure to drop below the formation closure pressure. At this point, there is no more extra pressure energy to hold the fractures open, which leads to a closing action of the formation mitigated by proppant particles that carry the stresses of formation closure (Liang et al., 2015). **Fig. 2** demonstrates the propped fracture.

The primary indicator, which characterizes the fracturing treatment, is the fracture conductivity calculated as the product of fracture width and proppant pack permeability. The well productivity after hydraulic fracturing is affected by the interaction between proppants and fracture surface under closure pressures; the proppants embed into the formations and deform due to the closure stress, resulting in a significant reduction in fracture conductivity. Investigating the factors influencing the fracture conductivity is a relatively complete task because either the treatment specifics or the reservoir features impact the result. E.g., proppant size, Young's modulus, and Poisson's ratio of the proppant and the formation and closure pressure are factors that influence proppant embedment and the change of fracture aperture, which can reduce the fracture conductivity by 99 % with a subsequent reduction in oil or gas production. Since the above-described situation affects fracture conductivity significantly, it is crucial to model the problem comprehensively.

Fig. 2 Illustration of a propped fracture (Terracina & Harper, 2018)

Therefore, the Author developed a state-of-the-art method to model in-situ fracture behavior by coupling DEM-FEM-CFD numerical solutions with the consideration of fundamental factors, such as fracture geometry, proppant geometry, proppant size, uneven proppant arrangement, proppant size distribution, deformation, embedment, and fluid dynamics. The potential application of the research conducted and summarized in the Thesis is the better understanding of propped fracture dynamics which may result in a more efficient fracturing treatment design for engineers working in the upstream division of the petroleum industry.

1.1. Research purpose & research conducted

The Author's research activity regarding hydraulic fracturing began in 2013 and focused on fracture conductivity in 2016. From the very beginning, the research path was well-defined based on the Author's previous experience: investigating fracture conductivity in a microscale environment and describing the propped fracture behavior in a more sophisticated way than found in the literature.

The first period of the research activity was characterized by a comprehensive literature review, which resulted in perspicuous research perspectives and goals. The literature review provided the author with an overall picture of experimental, analytical, semi-analytical, and numerical research conducted regarding fracture conductivity and brought out exact research aims as listed below:

- Pointing out conductivity influencing factors by performing analytical analysis and showing parameters' relevance.
- Developing an innovative numerical method to describe propped fracture dynamics with sufficient accuracy for technical practice, i.e., the evolvement of a coupled numerical method integrating the fracture and proppant geometry, proppant size and size distribution, uneven proppant arrangement, deformation, embedment, and fluid dynamics.
- Analyzing the one-way coupled numerical model results and comparing analytical and numerical findings with a particular focus on drawing relevant consequences.

- Carrying out experimental measurement using API standards and validating the model based on the results.

The analytical model, used to understand the physics behind fracturing and highlight relevant factors, can determine the proppant embedment, proppant deformation, and the sum of these: the change in fracture aperture. The fracture conductivity can also be computed by combining the Hertzian contact theory and the Kozeny-Carman capillary tube model. Using the analytical model, sensitivity tests could be accomplished to investigate the influence of factors. The results showed the crucial points where the emphasis should be put on.

The one-way coupling modeling technique developed by the Author's research activity incorporates the benefit of the Discrete — and Finite Element Method to describe the in-situ behavior of hydraulic fractures with specific consideration of fracture conductivity. DEM (Discrete Element Method) provided the application of random particle generation and non-uniform proppant placement. FEM (Finite Element Method) Static Structural module was used to simulate the elastic behavior of solid materials: proppant, and formation, while CFD (Computational Fluid Dynamics) solver was applied to define fluid dynamics within the propped fracture.

The numerical model results were compared to API RP-19D laboratory experiments conducted by the Author in the GEOCHEM Laboratory. The match of the outcomes validated the method and encouraged the Author to describe proppant deformation and embedment and their effect as precisely as possible. Furthermore, based on the results, sensitivity analysis was performed, which pointed out the impact of several factors affecting proppant embedment, deformation, and fracture conductivity and made one aware of a reasonable interpretation of propped hydraulic fracture operation.

The research techniques included all the conventional scientific solutions like:

- literature research to identify opportunities
- analytical model analysis to further concretize research perspectives
- numerical model development to describe the phenomenon
- laboratory experiments for model validation

The scientific achievements have been continuously published, and they are listed in **chapter 2 and 3**.

2. SCIENTIFIC ACHIEVEMENTS

Novel scientific results have been found during the research conducted and presented in the Ph. D. Thesis. This chapter summarizes the scientific findings and forms the theses.

2.1. Thesis #1

I developed a Discrete Element Model to describe the random proppant placement within the fracture. The gravitational drop makes the particles roll and slide on each other and contains tangential displacement components, i.e., enables interactions of both collision and friction. In addition, I incorporated inhomogeneity by applying particle geometry other than a sphere, shown in **Fig. 3**, and considering proppant size distribution, shown in **Fig. 4**. Finally, I verified the established model by the calibration procedure of a silo outflow experiment. The proppant's micromechanical properties are summarized in **Table 1**.

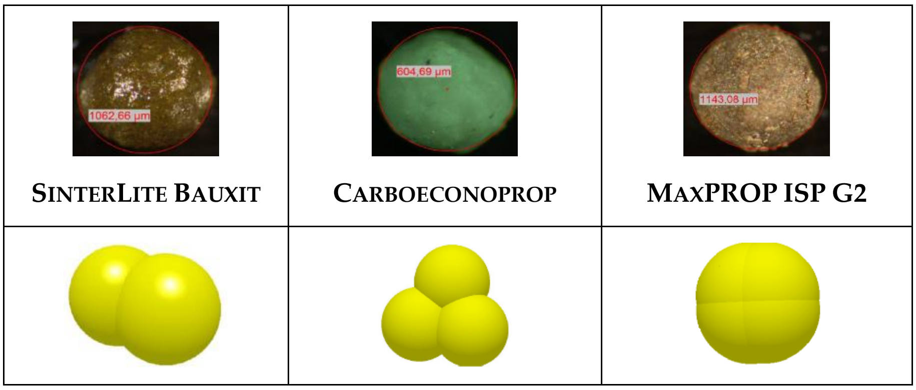

Fig. 3 Electron microscopic photos and DEM clumps

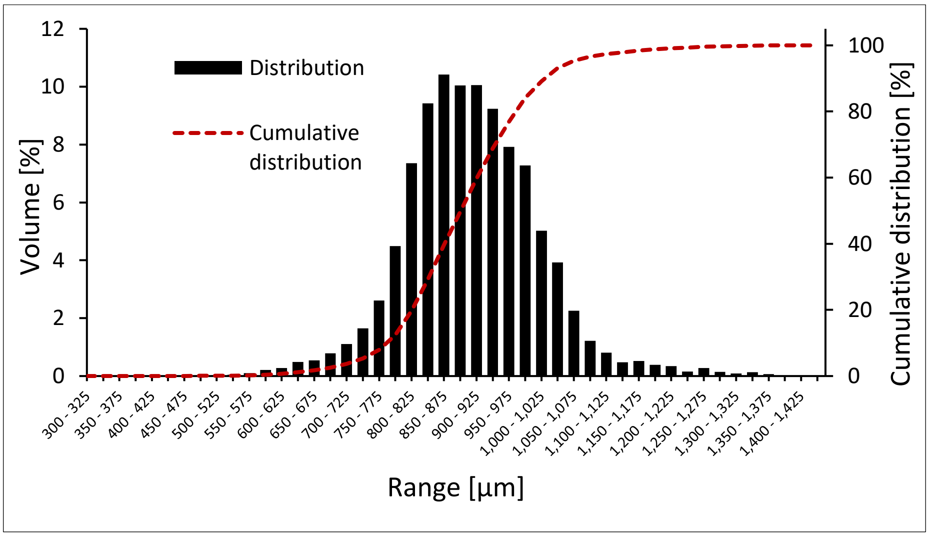

Fig. 4 Detailed size distribution of 16/30 proppant

Table 1. Calibrated micromechanical parameters

Parameter	Proppant	Silo
Poisson-ratio, ν [-]	0.25	0.3
Young modulus, E [Pa]	$4.13 \cdot 10^{10}$	-
Density, ρ_e [kg/m$^{3]}$	2800	5100
Friction angle, φ [°]	10	1
Coeff. of rolling friction, f [m]	0.0001	0

2.2. Thesis #2

I established a complex Finite Element Model (Structural and Computational Fluid Dynamics) to determine the proppant deformation and embedment into the hydrocarbon-bearing formation, shown in **Fig. 5,** and to simulate and investigate the fluid dynamics within the fracture inside the porous media formed by the compacted proppant pack.

I proved the validity of the Structrural and Computation Fluid Dynamics model, based on the standard API RP 19D. The results showed an excellent matching, shown in **Fig. 6** and **Fig. 7**, enabling me to examine fluid flow and determine the pressure drop across the domain examined. Based on this new method, the primary outcome of the hydraulic fracturing treatment – the fracture permeability and conductivity – can be determined.

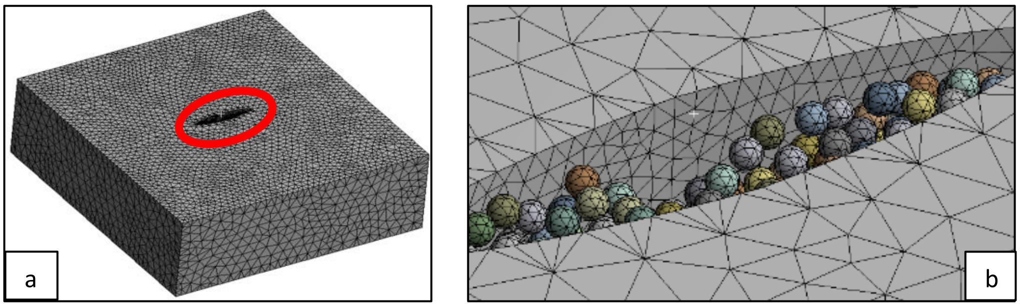

Fig. 5 Numerical mesh of the formation (**a**) and proppant particles (**b**).

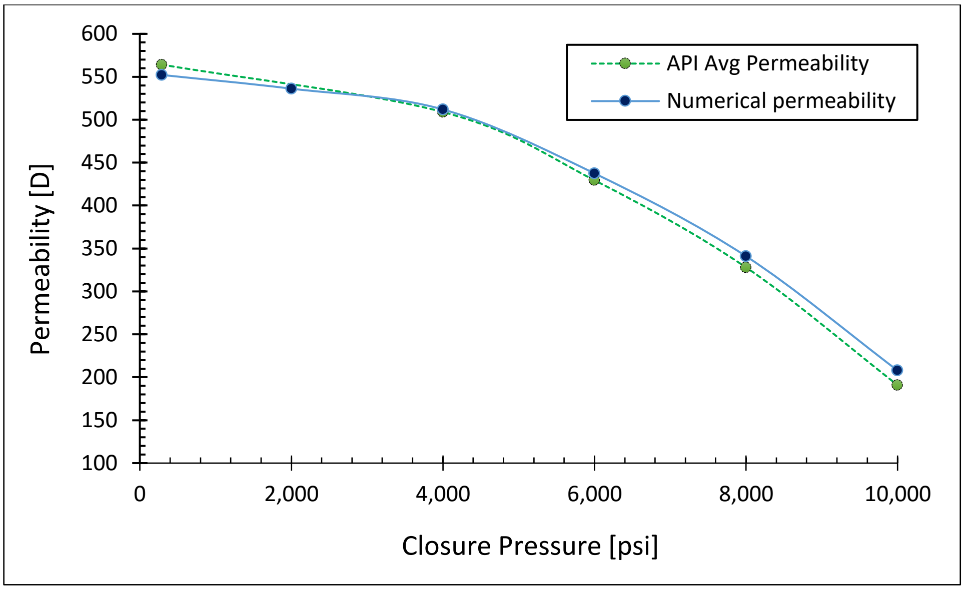

Fig. 6 API + numerical permeability

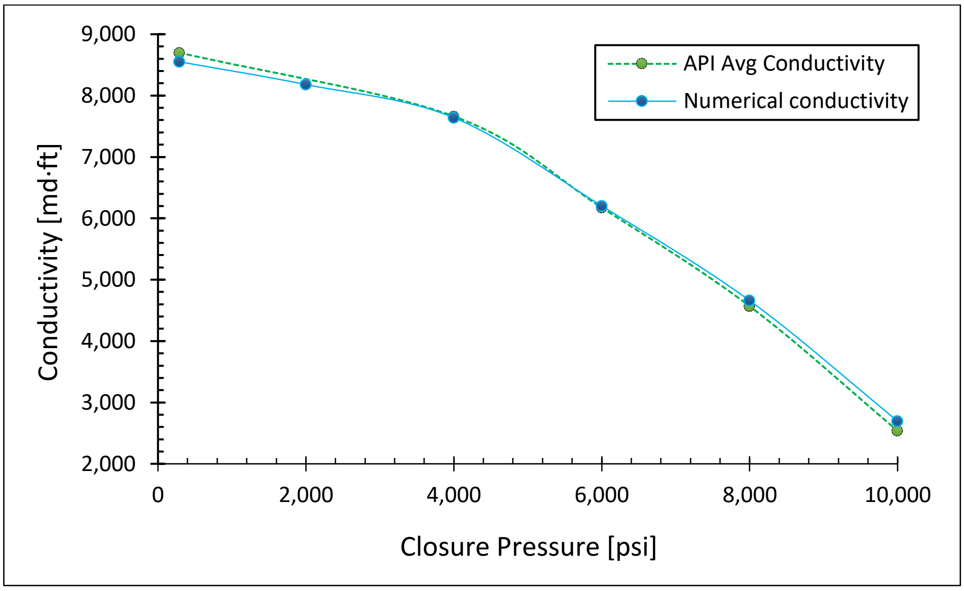

Fig. 7 API + numerical conductivity

2.3. Thesis #3

I evolved the one-way coupling method, demonstrated in **Fig. 8**, to establish an interface of DEM-FEM-CFD simulation and incorporate the benefits of different numerical approaches. Based on the method, complex mechanical analysis of propped hydraulic fractures can be performed. The established method can be interpreted as my primary research achievement and can be a pioneering technique for practicing field engineers.

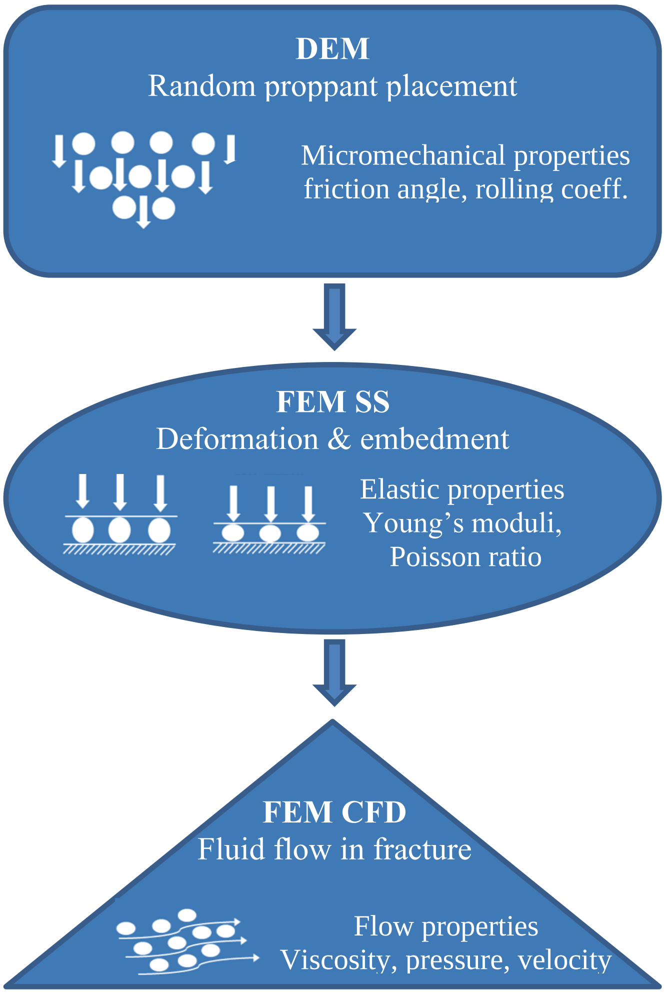

Fig. 8 Process flow developed

2.4. Thesis #4

Based on the one-way coupling method, I found that the initial fracture aperture hurts the proppant pack porosity and, therefore, the permeability, shown in **Fig. 9**. However, **Fig. 10** shows that the fracture conductivity increases with the initial fracture width; due to the higher degree of freedom, the proppant particles are forced to be arranged more orderly, entailing less interconnected effective porous space between the particles for fluid flow.

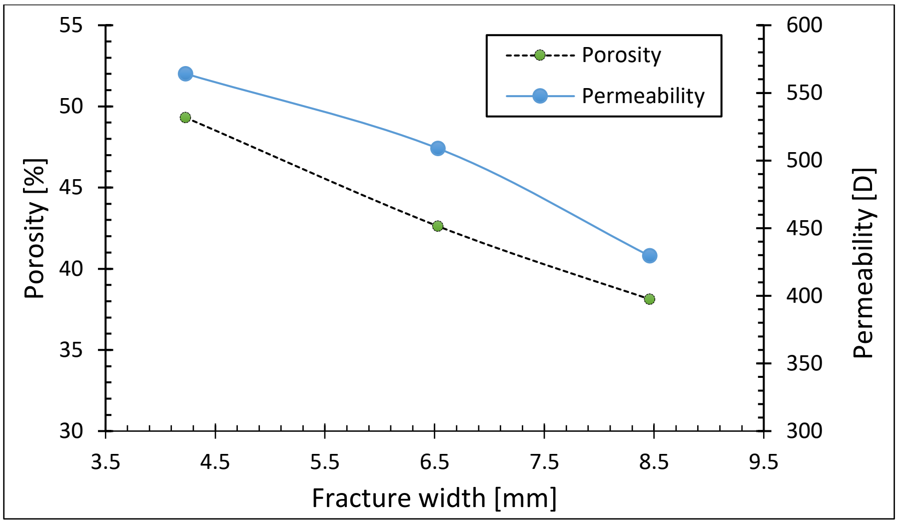

Fig. 9 Porosity and permeability as the function of fracture width

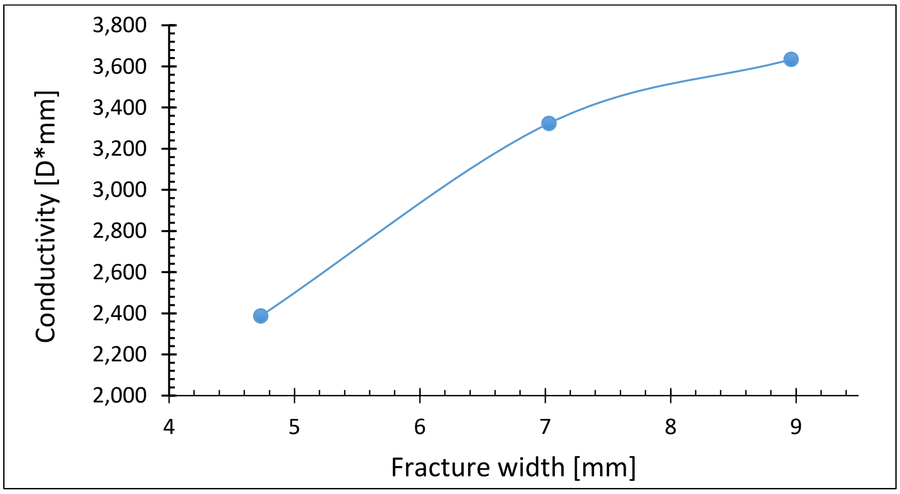

Fig. 10 Conductivity as the function of fracture width

2.5. Thesis #5

I showed the application of clumps (**Fig. 3**) to develop non-regular elements – differing from spheres – in DEM. **Fig. 11** demonstrates the results of clump application regarding porosity and permeability. The analysis highlighted the combination of four spheres to substitute spheroidal particles; however, it was excluded from the further investigation because of the slight impact on porosity and permeability with conspicuous time-consuming computational requirements.

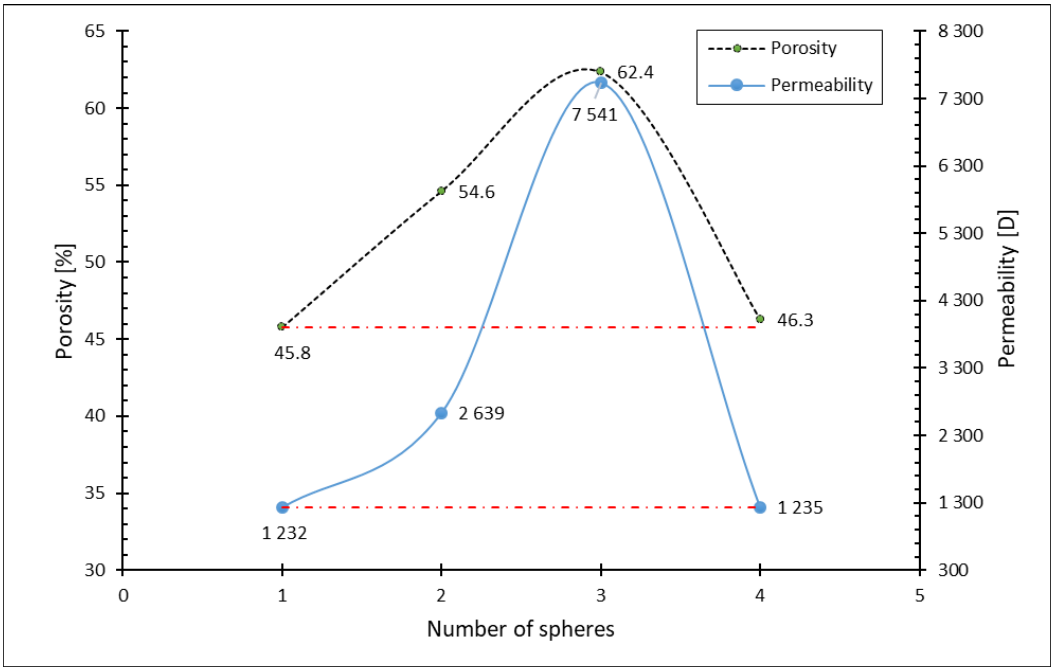

Fig. 11 Porosity and permeability for clumps

2.6. Thesis #6

I proved that the proppant geometry impact on fracture conductivity is less significant than the effect of particle size distribution. This finding confirms the geological and rock mechanics theory, i.e., the less sorted the granular media – it consists of more ranges of particle diameter – the less porosity can be reached based on the phenomenon of smaller fragments might be placed within the pore throat of larger particles. Nevertheless, this analysis also found that the tiny particles restrict the pore throat concerning fluid flow and provide support against fracture closure resulting thicker fracture aperture. **Fig. 12** and **Fig. 13** summarize the results, where the legend assigns *[mesh]* for the model results with size distribution, demonstrated with a dashed line, and *S mesh* for the uniform spheres, presented with a solid line.

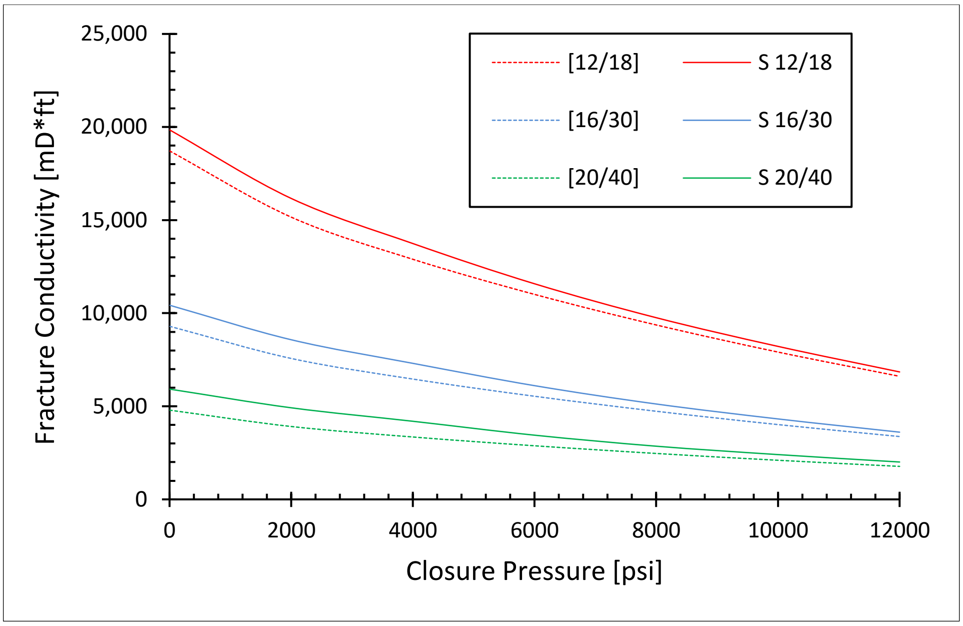

Fig. 12 Fracture Conductivity

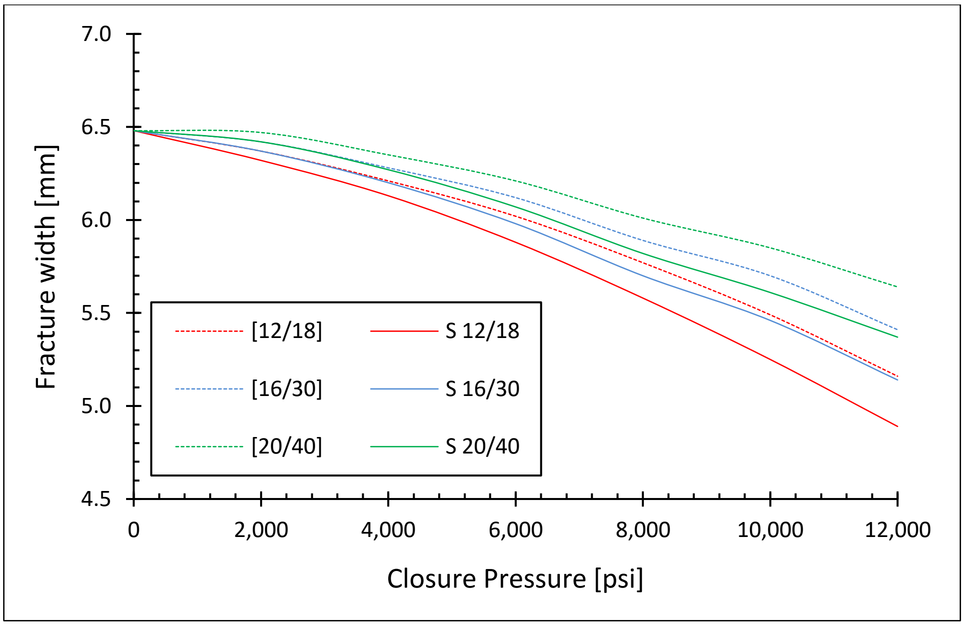

Fig. 13 Fracture Aperture

2.7. Thesis #7

Based on the research, I demonstrated the limits of the analytical model introduced by Li et al. (2015) and I draw the following conclusions:

- The analytical model supposes perfect spheres with the same diameter for all the particles; however, the granular media is sorted by sieves with a given size distribution, and their shape is characterized by sphericity and roundness indices.
- It assumes no friction between the particles, i.e., no tangential displacement component – friction traction – is considered.
- The Hertz model supposes the contact surface developed between the contacting objects is flat; however, the stiffer body domes into the softer object.
- The analytical solution is based on infinitesimal strain assumptions, which may conclude errors due to geometrical nonlinearities of finite deformation.
- Another limiting factor is the assumption of the Kozeny-Carman model, i.e., it is only valid for laminar flow.
- It applies the most compact, even proppant arrangement, i.e., the maximum achievable initial porosity is 0.259, which is not valid for most cases.

2.8. Potential application

The research demonstrated the capability of DEM-FEM-CFD coupling for modeling multidisciplinary processes regarding hydraulic fracturing and provided insight into the factors that drive the complex interactions between proppant particles, formation stiffness, and closure pressure. The outcome of this research may advance the fundamental understanding of proppant embedment and deformation and contribute to a broad scale of applied sciences that aim to optimize hydraulic fracturing.

The novel modeling technique, the one-way coupled method, enables the practicing engineers to integrate all relevant principle into the model and provide a huge potential to investigate fundamental parameters affecting the propped hydraulic fracture behavior. As CFD was successfully coupled, fluid dynamics could give place for further research directions, e.g., the turbulence and inertial impact of proppant geometry to be examined.

3. PUBLICATIONS PRESENTED IN THE THESIS' TOPIC

3.1. Articles and proceedings

Pusztai, P., Lengyel T. (2015): A Hidraulikus Rétegrepesztés Gazdasági Optimalizációja, Diáktudomány c. kiadvány, VIII. kötet, ISSN 2062-07-21, Miskolc, 2015.

Jobbik, A., Lengyel, T., Pusztai, P. (2015): Összetett Matematikai Modell Hidraulikus Rétegrepesztés Optimalizálására, Miskolci Egyetem Műszaki Földtudományi Közlemények Kőolaj és Földgáz kötet 85, pp. 97-105., ISSN 2063-5508, Miskolc, 2015.

Jobbik, A., Lengyel, T., Pusztai, P. (2016): An Innovative Method for Hydraulic Fracturing Optimization, Proceedings of the 4th International Scientific Conference on Advances in Mechanical Engineering (ISCAME 2016), pp. 302-307., ISBN:978-963-473-944-9, Debrecen, 2016.

Lengyel, T., Jobbik, A. (2017): Kombinált Analízis Rendszer a Proppant Kiválasztás Optimalizálására, Műszaki Tudomány Az Észak-Kelet Magyarországi Régióban, Elektronikus Műszaki füzetek, ISBN 978-963-7064-35-7, Nyíregyháza, 2017.

Lengyel, T. (2017): Repedés Konduktivitást Befolyásoló Tényezők Vizsgálata, Diáktudomány c. kiadvány, X. kötet, ISSN:2062-07-21, Miskolc, 2017.

Lengyel, T., Jobbik, A. (2020): Combined Analysis System for Proppant Selection in Aspect of Fracture Conductivity, Geosciences and Engineering, a Publication of the University of Miskolc (Miskolc University Press). HU ISSN 2063-6997, Miskolc, 2020.

Lengyel T., Jobbik, A. (2017): Integrated Model for Proppant Selection Optimization, Proceedings of 13th International Conference on Heat Engines and Environmental Protection, ISBN: 978-963-420-907-2, Budapest, 2017.

Lengyel, T., Jobbik, A. (2017): Proppant Optimalizálás a Repedés Konduktivitást Befolyásoló Tényezők Figyelembe Vételével, Miskolci Egyetem Műszaki Földtudományi Közlemények, ISSN 2063-5508, Miskolc, 2017.

Lengyel, T., Jobbik, A., Tóth, A. (2018): An Analytical Approach for Propped Fracture Conductivity, 18th International Multidisciplinary Scientific Geoconference – SGEM 2018 Conference Proceedings, Volume 18, Science and Technologies in Geology, Exploration and Mining, Issue 1.4, ISBN 978-619-7408-38-6, ISSN 1314-2704, DOI: 10.5593/sgem2018/1.4, Sofia, Bulgaria, 2018.

Lengyel, T. (2018): “Analytical Approach for Propped Fracture Conductivity”, Conference Proceedings of Spring Wind 2018 Conference, ISBN 978-615-5586-31-6, DOI: 10.23715/TSZ.2018.1, Budapest, 2018.

Pasztor, A., Lengyel, T. (2019): Method to calculate apparent permeability of hydraulic fractures. International Multidisclipinary Scientific Geoconference 19, 19(1.2), pp. 985-992., ISBN: 978-619-7408-77-5, ISSN: 1314-2704, Sofia, Bulgaria, 2019.

Varga, A., Lengyel, T., Safranyik, F. (2020): Determination of micromechanical parameters of proppant particles, International Journal of Innovative Research in Advanced Engineering, (2349-2163): 7 2 pp 15-21, 2020

Lengyel, T., Varga, A. (2020): Proppant szemcsék kifolyásvizsgálata, Miskolci Egyetem Műszaki Földtudományi Közlemények, ISSN 2063-5508, Miskolc, 2020.

Lengyel, T., Varga, A. (2021): Proppant szemcsék mikromechanikai paramétereinek meghatározása, Mérnöki és Informatikai Megoldások, https://doi.org/10.37775/EIS.2021.1., 2021

Lengyel, T.; Varga, A.; Safranyik, F.; Jobbik, A. (2021): Coupled Numerical Method for Modeling Propped Fracture Behavior. *Appl. Sciences.* 2021, *11*, 9681. https://doi.org/10.3390/app11209681

3.2. Conference presentations

Numerical Modeling of Proppant Deformation and Embedment, 5th ICSTR Singapore – International Conference on Science & Technology Research, Singapore, 26-27 March, 2021

Modeling Proppant Deformation and Embedment, 23rd International Conference on Multidisciplinary Studies "Resilience for Survival", Cambridge, 30-31 July 2020

Apparent Permeability of Fractures, 6th Annual Student Energy Congress – ASEC 2019, SPE Student Chapter, University of Zagreb, Zagreb, 2019

Analytical Approach for Propped Fracture Conductivity, Tavaszi Szél Konferencia, Győr, 2018

An Analytical Approach for Propped Fracture Conductivity, 18th International Multidisciplinary Scientific Geoconference – SGEM 2018 Conference, Sofia, 2018

Combined Analysis System for Proppant Selection in Aspect of Fracture Conductivity, XXXI. Nemzetközi Olaj- és Gázipari Konferencia, Siófok, 2017

An Innovative Method for Hydraulic Fracturing Optimization, 4th International Scientific Conference on Advances in Mechanical Engineering, Debrecen, 2016

Investigation of parameters influencing fracture conductivity including proppant pack properties and rock mechanical characteristics, „Új kutatási irányok a földi energiaforrások hasznosításához kapcsolódóan" című szakmai tudományos konferencia, Miskolc, 2017

Barents Sea – Eastern Finnmark Platform, AAPG - Imperial Barrel Award, Prague, 2017

Integrated Model for Proppant Selection Optimization, 13th International Heat Engines and Environment Protection Conference, Budapest, 2017

Kombinált Analízis Rendszer a Proppant Kiválasztás Optimalizálására, Műszaki Tudomány az Észak-kelet Magyarországi Régióban, Nyíregyháza, 2017

4. REFERENCES

Barree, R., Conway, M. (1995): Experimental and Numerical Modeling of Convective Proppant Transport (includes associated papers 31036 and 31068). J. Pet. Technol. 1995, 47, p. 216–222, https://doi.org/10.2118/28564-pa.

Barree, R., Cox, S., Barree, V., Conway, M. (2003): Realistic Assessment of Proppant Pack Conductivity for Material Selection. Soc. Pet. Eng., https://doi.org/10.2118/84306-ms.

Cooke, C.J. (1973): Conductivity of Fracture Proppants in Multiple Layers. J. Pet. Technol. 1973, 25, p. 1101–1107, https://doi.org/10.2118/4117-pa.

Denney, D. (2010): Thirty Years of Gas-Shale Fracturing: What Have We Learned? J. Pet. Technol. 2010, 62, p. 88–90, https://doi.org/10.2118/1110-0088-jpt.

Economides, M., Nolte, K. (2000): Reservoir Stimulation, 3rd ed. (John Wiley and Sons: Hoboken, NJ, USA, 2000) ISBN 978-047-149-192-7

Fredd, C., McConnell, S., Boney, C., England, K. (2000): Experimental Study of Hydraulic Fracture Conductivity Demonstrates the Benefits of Using Proppants. Soc. Pet. Eng. 2000, https://doi.org/10.2118/60326-ms.

Huitt, J.L., McGlothlin, B.B. (1958): The Propping of Fractures in Formations Susceptible to Propping-sand Embedment, Paper presented at the spring meeting of the Pacific Coast District, Division of Production, Los Angeles, California, May, 1958. SPE-58-115-MS. http://dx.doi.org/10.2118/58-115 MS.

Lehman, L.V., Parker, M.A., Blauch, M.E., Haynes, R., Blackmon, A. (1999): Proppant Conductivity—What Counts and Why. Soc. Pet. Eng., https://doi.org/10.2118/52219-ms

Li, K., Gao, Y., Lyu, Y., Wang, M. (2015): New Mathematical Models for Calculating Proppant Embedment and Fracture Conductivity. SPE J., 20, p. 496–507, https://doi.org/10.2118/155954-pa.

Liang, F., Sayed, M., Al-Muntasheri, G., Chang, F.F. (2015): Overview of Existing Proppant Technologies and Challenges. Soc. Pet. Eng., https://doi.org/10.2118/172763-ms.

McDaniel, G.A., Abbott, J., Mueller, F.A., Mokhtar, A., Pavlova, S., Nevvonen, O., Parias, T., Alary, J.A. (2010): Changing the Shape of Fracturing: New Proppant Improves Fracture Conductivity. Soc. Pet. Eng., https://doi.org/10.2118/135360-ms.

Milton-Tayler, D., Stephenson, C., Asgian, M. (1992): Factors Affecting the Stability of Proppant in Propped Fractures: Results of a Laboratory Study. Soc. Pet. Eng., https://doi.org/10.2118/24821-ms.

Peard, N., Macaluso, M., Griffin, M., Andress, R., Callanan, M. (1991): Improved Fracturing Techniques Increase Productivity in the AWP (Olmos) Field. Soc. Pet. Eng. https://doi.org/10.2118/21646-ms.

Roodhart, L., Kulper, T., Davies, D.R.K. (1988): Proppant-Pack and Formation Impairment during Gas-Well Hydraulic Fracturing. SPE Prod. Eng., 3, p. 438–444, https://doi.org/10.2118/15629-pa.

Weaver, J.D., Rickman, R.D., Luo, H. (2008): Fracture-Conductivity Loss Due to Geochemical Interactions between Manmade Proppants and Formations. Soc. Pet. Eng., https://doi.org/10.2118/118174-ms.